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Moisture-induced stresses and distortions in spruce cross-laminates and composite laminates

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Abstract

The crosswise gluing of cross-laminated panels made of solid wood can cause problems when exposed to moisture variations. In the present study, the substitution of the spruce middle layer by a wood composite is tested for its influence on moisture-induced stresses and deformations in laboratory tests and numerical simulations. Furthermore, slits in the spruce middle layer were investigated. The hygroscopic warping due to a moisture gradient, stresses caused by moistening and cracks due to drying were studied. The results show larger warping in composite laminates compared to the spruce cross-laminate, which is governed by the modulus of elasticity of the middle layer. The in-plane swelling was found to be larger in composite laminates, while stresses were lower. The drying test discovered that cracks develop in the middle layer of spruce-medium density fiberboard laminates due to shear stresses and tensile stresses in the thickness direction. It was concluded that slits can be applied in the middle layer, as they have no significant influence on moisture-induced stresses but increase the thermal insulation. If the substitution of the spruce layer is required, the application of oriented strand board in the middle layer is recommended.

Keywords: cross-lamination; eigenstress; FEM; medium density fiberboard (MDF); moisture; oriented strand board (OSB); particleboard; spruce (*Picea abies*); warping.

Introduction

Moisture-induced deformations and stresses play an important role in the application of cross-laminated wood panels. In the present study, these deformations and stresses were investigated by means of experimental tests and numerical simulations of spruce cross-laminates and composite laminates. Unlike previous studies (Gereke et al. 2009a), the spruce middle layer was substituted by wood composites. This weakens the middle layer compared to spruce in the longitudinal direction of the solid wood variant. The application of wooden composites in the core layer allows for reduced production costs. Wood-based panels are characterized by a more homogeneous property distribution in the in-plane directions than solid wood, where the differences between properties parallel and perpendicular to the fiber alignment are very large. Slits in the spruce middle layer were also tested. According to Bader et al. (2007), gaps increase the thermal insulation. This is advantageous for practical applications.

Gereke et al. (2009a) evaluated the moisture distribution within three-layered cross-laminates made of spruce wood and the hygroscopic warping induced by a moisture gradient was studied. The authors also examined the diffusion coefficient of the polyurethane glue lines and validated a three-dimensional mechanical material model against moisture-induced deformations of cross-laminated spruce panels.

Tobisch (2006) tested the dimensional stability of 500 mm×500 mm large cross-laminated solid wood panels exposed to a moisture gradient in a double climate chamber. The tests of different middle layer materials showed that spruce panels were more stable to warp than panels where the middle layer was substituted by particleboard (PB) or oriented strand board (OSB). A substitution with plywood yielded lower warping but is too expensive for practical applications. Systematic cross-laminated layers were more stable to warp than panels without cross-lamination. Cross-lamination describes the fact that the 1-axis of the wood composite middle layer (Figure 1a) is aligned parallel to the *y*-axis of the panel coordinate system (Figure 1b).

In the present study, the substitution of the spruce middle layer by a wood composite [OSB, PB, medium density fiberboard (MDF)] should be tested in terms of its influence on moisture-induced stresses and deformations in laboratory tests and numerical simulations. Furthermore, slits in the spruce middle layer (cut by a circular saw) will be investigated. Three moisture scenarios, which cause problems in practice were examined: hygroscopic warping due to a moisture gradient, internal stresses caused by moistening, and cracks due to drying (Table 1).

Material

Spruce (*Picea abies* L.) outer layers were combined with different middle layers. The outer layer thickness of the three-layered panels was constant at 10 mm. The individual layers were assembled in

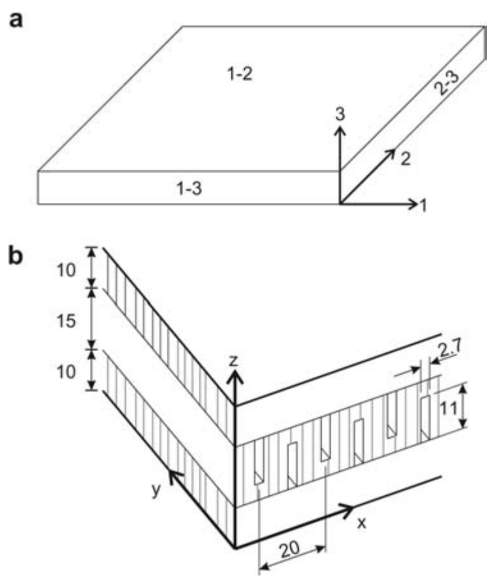

Figure 1 (a) Schematic drawing of an MDF specimen with definition of coordinate system: 1 – production direction, 2 – perpendicular to production direction, 3 – thickness direction. (b) Characteristics of panels with slitted middle layers and panel coordinate system, dimensions in mm.

the laboratory with one-component polyurethane (Purbond HB110, Purbond AG, Sempach Station, Switzerland). The following processing parameters were applied: amount of adhesive application: 200 g m^{-2}; forming pressure: 0.8 N mm^{-2}; pressing time: 3 h. Spruce middle layers with a thickness of 15 mm were tested in two variations: with and without slits. Slits were sawn into the middle layer by means of a circular saw. As shown in Figure 2, they were aligned in the fiber direction and alternated from the top to the bottom side of the layer.

The characteristics of wood composite middle layers are summarized in Table 2. OSB, PB, and two types of MDF were applied: MDF500 and MDF700. They varied in their density. The layer ratio

$$LR = \frac{2a_{OL}}{a_{tot}}, \tag{1}$$

which is the thickness of the two outer layers, a_{OL} [m], as a percentage of the total thickness, a_{tot} [m], was 0.56 and 0.57, respectively.

Methods

Table 1 shows the investigated moisture scenarios and the panel dimensions. The shape stability (warping) was determined by inducing a moisture gradient within the panels. The test method is shown in greater detail in Gereke et al. (2009a). Two cup deformations were calculated according to Gereke et al. (2009a): cup_{xz} and cup_{yz}. These terms refer to cupping along the *x*-axis (parallel to the fiber direction of the outer layers, Figure 2) and the *y*-axis (perpendicular to the fiber direction of the outer layers).

The internal stress state was studied in experiments where panels were exposed to a single moistening step (Table 1). At several sampling points, 25 mm of all edges were removed to prevent influences of unhindered swelling of the boundaries. Subsequently, the panels were sawn into strips and cut along the glue lines. Stresses were determined from the released strains and dynamic determination of the modulus of elasticity (MOE), as established earlier (Gereke et al. 2009b).

In drying tests, the previously moistened panels were exposed to a dry climate (Table 1). The length of cracks on the panel surfaces were measured and added for each panel.

Numerical simulations of spruce cross-laminates and spruce-MDF laminates completed these experimental tests. A one-dimensional material model based on Fick's law of diffusion – as established in Gereke et al. (2009a) – was used to simulate the moisture distribution. The relationship between moisture content ω [-] and the diffusion coefficient of the glue lines, D_{adh} [m^2 s^{-1}], was evaluated by Gereke et al. (2009a) to be

$$D_{adh}(\omega) = C_1 \cdot \omega^{-C_2} + C_3. \tag{2}$$

The shape factors are $C_1 = 9.17 \cdot 10^{-12}$ m^2 s^{-1}, $C_2 = 0.51$ [-] and $C_3 = -2.39 \cdot 10^{-12}$ m^2 s^{-1} (Gereke et al. 2009a). The diffusion coefficient of MDF, D [m^2 s^{-1}], which is applied in the present simulations was determined by Ganev et al. (2003) for different nominal densities ρ [kg m^{-3}] in adsorption to be

$$D_{\rho=540}(\omega) = 2 \cdot 10^{-6} e^{-1.1466\omega}$$
$$D_{\rho=800}(\omega) = 2 \cdot 10^{-8} e^{-0.7483\omega} \tag{3}$$

Since air velocity was slow in the experimental tests, the external surface resistance of wood was taken into consideration in the moisture model. The mass transfer coefficient h [m s^{-1}] proposed by Hanhijärvi (1995) was applied:

$$h(\omega) = 3.2 \cdot 10^{-8} e^{4\omega} \tag{4}$$

An orthotropic mechanical material model considering elastic deformation, moisture-induced swelling and mechano-sorptive deformation was applied to the spruce layers. This model was previously validated by Ormarsson (1999) and Gereke et al. (2009a), where the material data are given. The adhesive layer with a thickness of 0.1 mm was assumed to act as a linear elastic material with $E_{adh} = 470$ MPa and $\nu_{adh} = 0.3$ (Konnerth et al. 2007). Plane isotropic properties were assumed for the MDF middle layer with iden-

Table 1 Investigated moisture scenarios (T=20°C).

Scenario	Initial RH (%)	Test RH (%)	Investigated property	Panel dimension (mm)
Moisture difference	65	65/100 (upper/lower surface)	Warping	300×300
Moistening	35	65 (all surfaces)	Eigenstresses	250×250
	35	85 (all surfaces)	Eigenstresses	
Drying	85	35 (all surfaces)	Cracking	500×500

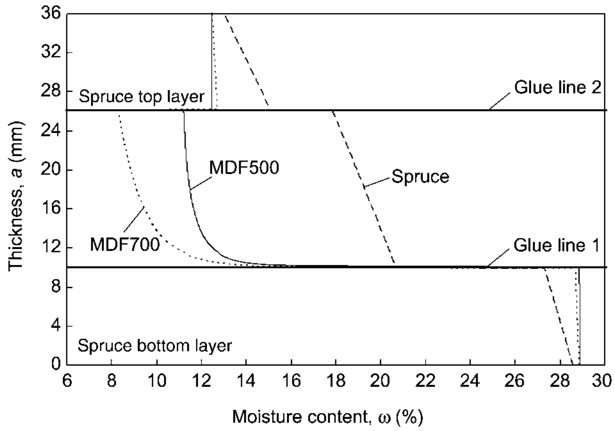

Figure 2 Simulated moisture profiles of spruce cross-laminate and two spruce-MDF laminates caused by 2000 h of moisture difference 65% RH (top face) and 100% RH (bottom face).

Table 2 Characteristics of the tested wood composite middle layers.

Material[a]	Thickness (mm)	Density (kg m^{-3})	E_1 (N mm^{-2})[b]
OSB	16	620	4904
PB	15	650	2076
MDF500	15	530	1907
MDF700	16	710	3189

[a]Abbreviations: OSB, oriented strand board; PB, particleboard; MDF, medium density fiberboard.
[b]Modulus of elasticity in production direction according to tensile tests of Schreiber et al. (2007).

tical properties in the 1- and 2-directions (Figure 1a, Ganev et al. 2005b): $E_1 = E_2$ (moduli of elasticity), $G_{23} = G_{13}$ (shear moduli), $\nu_{12} = \nu_{21}$, $\nu_{23} = \nu_{32} = \nu_{13} = \nu_{31}$ (Poisson's ratios) and $\alpha_1 = \alpha_2$ (swelling coefficients). In the present simulations, MDF500 and MDF700 were tested. The numerical calculations of both materials were based on the input parameters of MDF with nominal densities of $\rho = 540$ kg m^{-3} (MDF500) and $\rho = 800$ kg m^{-3} (MDF700) given in Eq. (3) and Table 3. The mechanical and expansion properties of MDF shown in Table 3 significantly differ in the in-plane and the thickness direction:

$$E_1 \gg E_3\,;\alpha_1 \ll \alpha_3.$$

Results and discussion

Hygroscopic warping due to moisture gradient

The simulated moisture profiles reveal differences between the two types of MDF middle layers as displayed in Figure 2. The MDF500 middle layer is significantly moister than the MDF700 middle layer. On the one hand, this is caused by the differences in the diffusion velocity, which is quantified by the diffusion coefficients. They deviate between both materials, MDF500 and MDF700, as shown in Eq. (3). On the other hand, the differences in the moisture content (MC) of the middle layers are caused by the differences in the equilibrium moisture content (EMC). These strongly depend on the density, which differ between the two types of MDF. Furthermore, the EMC of MDF is significantly lower than that of spruce. The reasons include the different densities of MDF and spruce, the application of an adhesive system in MDF, and the production process of MDF:

- The adhesive blocks sorption sites of the fiber material, resulting in lower MC of MDF compared to spruce in the same climatic conditions. This yields significant moister spruce middle layers compared to the MDF middle layers in laminates.
- The drying of the wood fibers during the production of MDF also results in lower EMC similar to thermally treated wood.

Figure 4 shows the history plots of measured cup deformations, cup_{xz} and cup_{yz}. The major cupping direction is the yz-plane, as previously shown in Gereke et al. (2009a). The results indicate that the wood composites have a significant influence on warping and that the slitted middle layer has no significant influence on warping. The composite laminates showed substantially higher warp deformations than the spruce panels. This is due to the moisture profile as shown for MDF in Figure 3. The wood composite in the middle layer acts as a moisture barrier. The MC of the bottom layer is significantly higher in composite laminates than in spruce panels. Thus, the swelling of the bottom layer is higher, which results in a large cup_{yz}. Not all composite laminates reached an equilibrium state, i.e., constant warp deformation. Rather, their warp deformations increased during the data recording.

The largest cup deformations, cup_{yz}, were obtained for composite laminates containing PB and MDF500, while it was lower in MDF700- and OSB-composite laminates. Due

Table 3 Mechanical properties of MDF according to Ganev et al. (2005a,b,c), relationship between character x_{ij} $(i, j = 1, 2, 3)$ and moisture content ω (0.069…0.135): $x_{ij} = x_0 - x_m\omega$.

ρ (kg m^{-3})		E_1 (N mm^{-2})	E_3 (N mm^{-2})	G_{13} (N mm^{-2})	ν_{12} (-)	ν_{13} (-)	α_1 (%$\%^{-1}$)	α_3 (%$\%^{-1}$)
540	x_0	1017.0	31.5	60.5	0.3	0.2	0.017	0.74
	x_m	4250.2	220.1	113.4				
800	x_0	3081.9	119.4	237.4	0.3	0.2	0.036	0.84
	x_m	12563.2	842.5	1497.8				

to the deformation of the bottom layer, the whole panel is exposed to a bending deformation towards the minor axis (perpendicular to the fiber direction of the outer layers). Since the top layer has only a small MOE in that direction, it is only able to minimally constrain warp deformation of the panel. Thus, the ability to resist warp depends, to a great extent, on the ability of the middle layer to constrain the deformation of the bottom layer. Therefore, the MOE of the middle layer is of great importance. cup_{yz} is inversely proportional to the MOE of the middle layer, i.e., with increasing MOE, cup_{yz} decreases. Thus, the ratio $cup_{yz}/cup_{yz,spruce}$ strongly correlates with the ratio $E_{L,spruce}/E_1$ as indicated in Figure 4.

As presented in Table 4, cup deformations in the minor axis show similar characteristics when compared to results obtained by Tobisch (2006). Discrepancies between both investigations are a result of differences in the moisture gradients, the panel thicknesses, the layer ratios, the panel dimensions, and the positioning of the panels on the supports. However, the comparison of panels with similar layer ratios in spruce panels and composite laminates reveals larger cup deformations in composite laminates compared to the spruce panels in both investigations.

The results of mechanical material modeling are contrasted against the measured cup deformations in Table 5. The simulated warping shows good agreement to the measured data in both series, MDF500 and MDF700. The results clearly indicate that the spruce-MDF700 laminate is much more dimensionally stable than the spruce-MDF500 laminate.

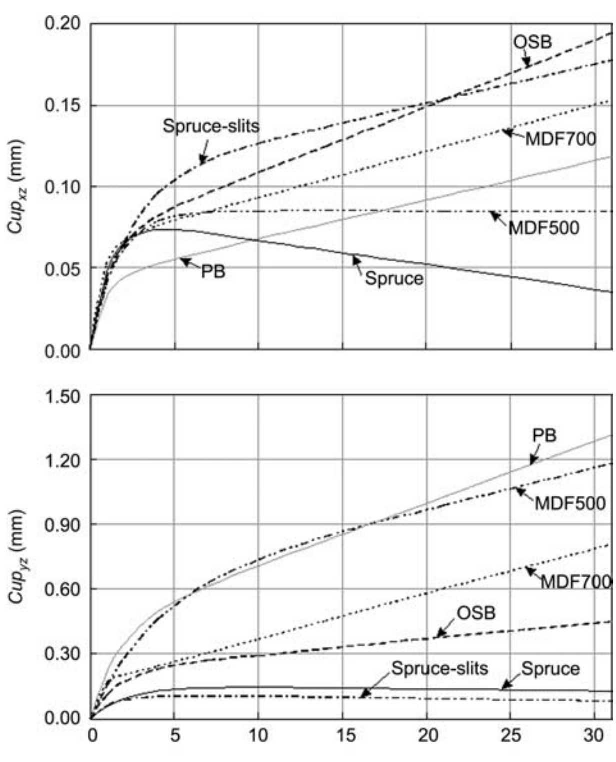

Figure 3 History plots of measured cup deformations caused by moisture difference 65%/100% RH, curves showing non-linear regression functions of average values ($cup=a\cdot(1-e^{-b\cdot t})+c\cdot t$).

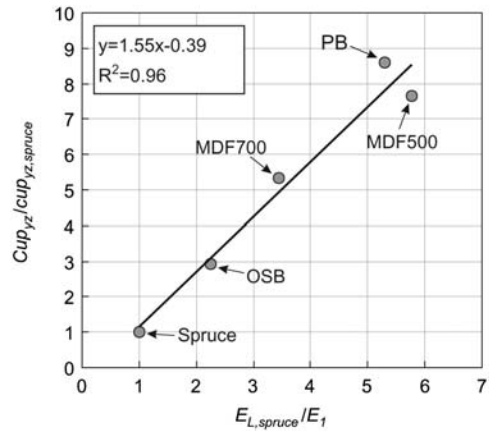

Figure 4 Relationship between modulus of elasticity (MOE) of the middle layer and measured cup_{yz}, MOE of spruce in the longitudinal direction ($E_{L,spruce}$) according to Sell (1997), MOE of wood composites in the production direction (E_1) according to Schreiber et al. (2007).

The numerical test of different layer ratios, with the total thickness kept constant, shows a linearly increasing cup_{yz} with increased LR. The cupping, cup_{xz}, is not greatly influenced when LR is varied, since the outer layers are the dominant layers for warping. With increased LR the relative thickness of the outer layers increases and, thus, cup_{yz} increases.

Internal stresses due to single moistening step

The history developments of stresses in the outer layers perpendicular to the grain are plotted in Figure 5 for the two test climates, 65% RH and 85% RH. In the initial state ($t=0$d), marginal tensile stresses were observed. Due to wetting, compressive stresses developed until the maximum, which was between day 5 and 7 in most of the panels. Afterwards, the compressive stresses remained constant or decreased until day 21. A distinct maximum was observed for MDF700 tested at 85% RH ($t=5$d). Due to large variations, significant tendencies between different panel structures were not detected.

To complete the experimental studies, four types of panels were compared numerically. In Table 6, the layer characteristics of the boards studied are presented. The investigation tested different layer ratios of spruce panels (S1 and S2) and different middle layer materials (MDF and spruce, panels S2–S4). The panels were assumed to be insulated at the ends and moisture transport was assumed to be one-dimensional in the cross-sectional direction. The relative humidity of the ambient air was increased from 35% to 85%. The dimension of the panels was 100 mm×100 mm. Due to double symmetry and appropriate boundary conditions this allowed simulating 200 mm×200 mm panels.

Figure 6 illustrates the history plots of moisture in the outer and middle layers. Each curve represents the MC of a

Table 4 Comparison of cup deformations along the y-axis observed in the present study to results obtained by Tobisch (2006) for panels with different middle layer materials, t=48 h.

Source	Middle layer	a_{tot} (mm)	LR (-)	Climate difference (%)	Moisture gradient (% mm^{-1})	Cup (%)
Tobisch (2006)	Spruce	27	0.67	35/85	1.85	100
	OSB	27	0.63	35/85	1.85	134
	PB	27	0.63	35/85	1.85	229
Present study	Spruce	35	0.57	65/100	1.00	100
	OSB	36	0.56	65/100	0.97	176
	PB	35	0.57	65/100	1.00	381

Table 5 Cup deformations in spruce-MDF laminates at t=744 h observed in experiments and obtained by simulation.

Middle layer material	Cup_{xz} (mm)		Cup_{yz} (mm)	
	Exp.[a]	Sim.[b]	Exp.[a]	Sim.[b]
MDF500	0.08 (0.06)	0.13	1.15 (0.25)	1.29
MDF700	0.15 (0.10)	0.15	0.80 (0.25)	0.79

[a]Mean value (standard deviation).

[b]MDF500 corresponds to MDF540 and MDF700 to MDF800 in Table 3.

node in the center of the layer. Strong differences in the MC of the middle layer are governed by thickness and material. The thinner the panel, the faster the middle layer saturates with moisture. Thus, the MC of board S1 increases faster than that of board S2, and the MC in the S2 middle layer adapts to the MC in board S1 with time. MC is also governed by material density and diffusivity in different materials. Thus, the MDF middle layers of boards S3 and S4 are significantly drier than the spruce middle layers of boards S1 and S2.

Figure 7 shows the history developments of the displacements u_y for a node at the unhindered edge ($y=z=0$ mm) in the center of the panel ($x=100$ mm). It is readily visible that deformation is larger in spruce-MDF laminates than in spruce cross-laminates. This is due to the lower stiffness and the slightly larger swelling of MDF compared to spruce in the longitudinal direction. Outer layers are hindered to a greater extent by a spruce middle layer than by an MDF middle layer. The swelling of panels S3 and S4 is governed by the density and, thus, moisture content, stiffness, and swelling coefficient of the MDF middle layer. Deformations in board S3 (MDF500) are larger than those of S4 (MDF700). The plots of stresses in the y-direction given in Figure 8 confirm these findings. Compressive stresses perpendicular to the grain in the outer layers are lower in composite laminates than in spruce cross-laminates, which is a result of the stronger constraint by the spruce core.

Drying test

In Table 7 the results of the drying test are listed. As illustrated in Figure 9a, cracks developed within one lamella or between two lamellas due to exceeding the tensile strength. Compared to the solid wood variant, spruce-PB- and spruce-OSB-laminates showed larger crack lengths. In panels with MDF middle layer, cracks were observed at the lateral faces in the MDF layer. They were aligned in the x-direction (Figure 9b). Depending on the manufacturing, MDF and also PB

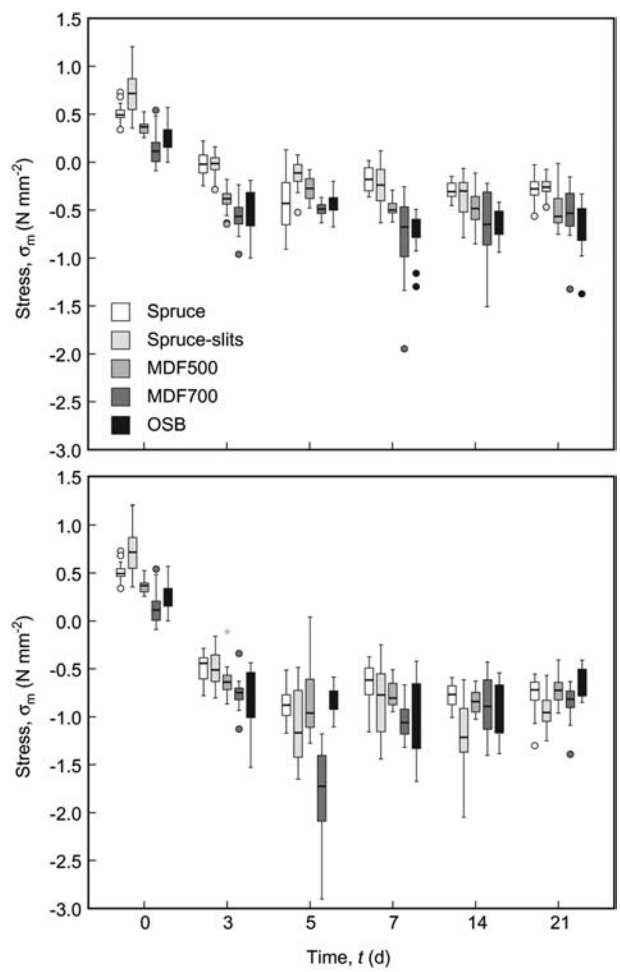

Figure 5 Measured average stresses in the outer layers perpendicular to the grain in two test climates, 65% RH (upper) and 85% RH (lower), initial climate 35% RH, the box and whisker plots show the median (*horizontal line in the box*), the 50% interquartile range (*box*), the 5% and 95% quartile (whiskers) and extreme values (*circle*).

Table 6 Characteristics of panels S1–S4.

	Outer layers		Middle layer		
ID	Material	a_{OL} (mm)	Material	a_{ML} (mm)	LR (-)
S1	Spruce	10	Spruce	10	0.67
S2	Spruce	10	Spruce	15	0.57
S3	Spruce	10	MDF500[a]	15	0.57
S4	Spruce	10	MDF700[a]	15	0.57

[a]Material data according to Table 2.

have a distinctive density profile in the thickness direction with a higher density in the outer parts and a low density in the core. The cracks were observed at the borders of low and high density. Shear stresses due to different shrinkage of outer and middle layers and tension in the thickness direction are the reasons for the cracks in the middle layer (Figure 9b).

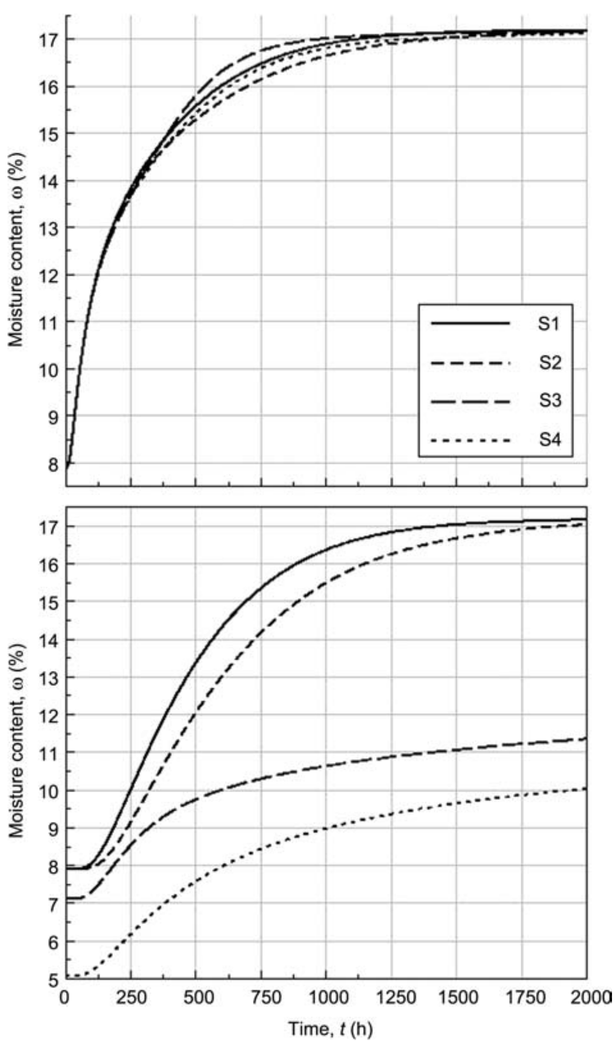

Figure 6 Simulated moisture content in the outer (upper) and middle layers (lower) in panels S1–S4 (Table 6), moistening from 35% RH to 85% RH at the large faces.

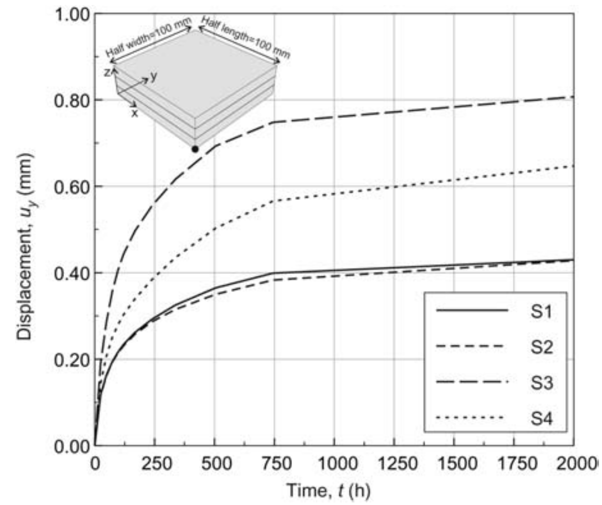

Figure 7 Simulated displacements in the y-direction (radial), u_y, in the outer layer, determined for panels S1–S4 (Table 6), wetting from 35% RH to 85% RH.

This release of stresses in the middle layer closed once opened cracks on the wood surfaces. This yielded fewer cracks on the large surfaces of spruce-MDF laminates. On the lateral faces of PB cracks were not detected which was a result of the furrowed surface.

Conclusions

Wood composite middle layers may be applied in industrial processes. Their advantages compared to solid wood are: reduced eigenstresses and reduced costs. Disadvantages are the higher weights of the panels, the cracking of the middle

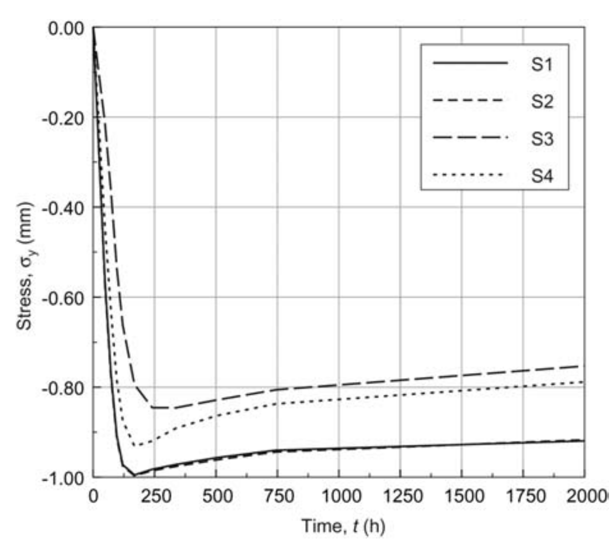

Figure 8 Simulated stresses in the y-direction (radial), σ_y, in the outer layer, determined for panels S1–S4 (Table 6), wetting from 35% RH to 85% RH.

Table 7 Crack length sum on the large surfaces of wood panels after 21 days drying from 85% to 35% RH, n=3.

Middle layer	Σ crack length (mm)
Spruce	96.7
MDF500	68.2
MDF700	67.0
OSB	267.5
PB	177.4

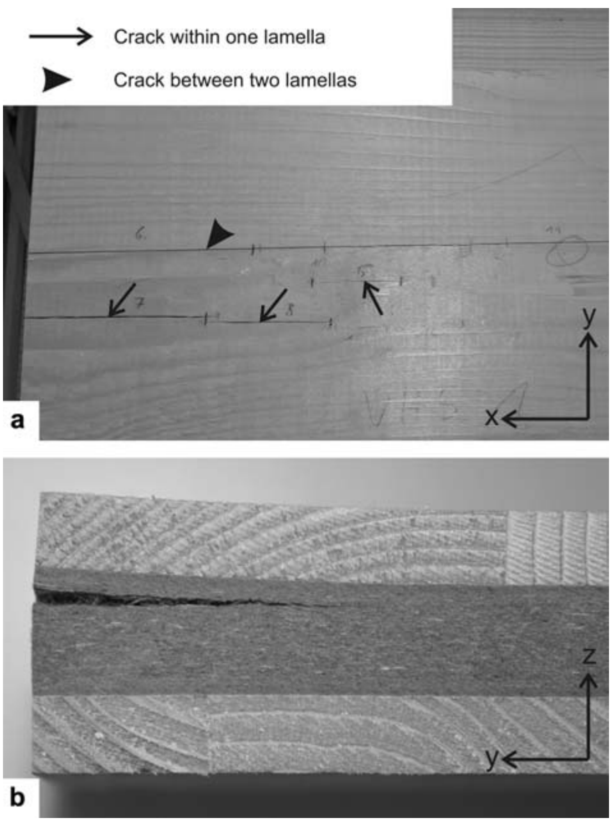

Figure 9 Cracks on the large surfaces (a) and crack on the lateral face of the middle layer of a spruce-MDF500 laminate (b).

layer during drying processes (MDF), and the larger expansion and contraction when the ambient climate changes. This may lead to problems in areas where two panels are connected, such as gap opening or failure due to compression. Composite laminates should, therefore, be investigated in large-sized sample tests. The cupping of boards with different middle layer materials is highly dependent on the MOE of the material used. Lower MOE causes larger cupping. Thus, the lowest cup deformations of composite laminates were found for panels consisting of OSB cores. It is, therefore, recommended to apply OSB in the middle layer if the substitution of the spruce layer is required. However, the warping of spruce cross-laminates is significantly lower than the warping of composite laminates, which is due to the differences in stiffness. Slitted middle layers show no significant effect on warping. After static bending tests they can be applied in industrial production if a larger thermal insulation is required.

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